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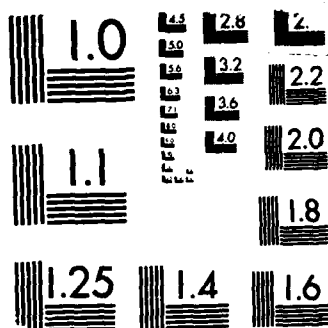
SPECTRAL LINE SHAPES FROM HIGHLY IONIZED SODIUM PLASMAS 1/1  
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# **Spectral Line Shapes from Highly Ionized Sodium Plasmas**

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# SPECTRAL LINE SHAPES FROM HIGHLY IONIZED SODIUM PLASMAS

## I. INTRODUCTION

In an effort to demonstrate coincidence photopumping of Ne IX ions with the Na X resonance line at 11.0 Å we studied Z-pinched plasma implosions of NaF puffs ejected from a capillary plasma gun (1) (2). The Naval Research Laboratory pulsed power generator Gamble II was used. The time integrated K-shell emission from these plasmas was recorded with two convex crystal spectrographs using a spatial imaging slit. In the first spectrograph a convex mica crystal was collecting all the sodium K-shell emission as shown in earlier publications ((2) Fig. 10) and a few fluorine lines. The second instrument used a slightly-curved (radius 10 cm) convex KAP crystal reflecting in second order that provided high-spectral resolution and minimum instrumental broadening (see below). The sodium transitions collected with this instrument between 11 and 8 Å are shown in Fig. 1. The spatially-resolved spectra displayed axial resolution of the plasma so that the line widths were determined at a number of positions along the axis corresponding to different regions along the Z-pinch. At these locations, we estimated the plasma diameter, from direct measurements of the plasma pinhole images of the total K-shell radiation (3).

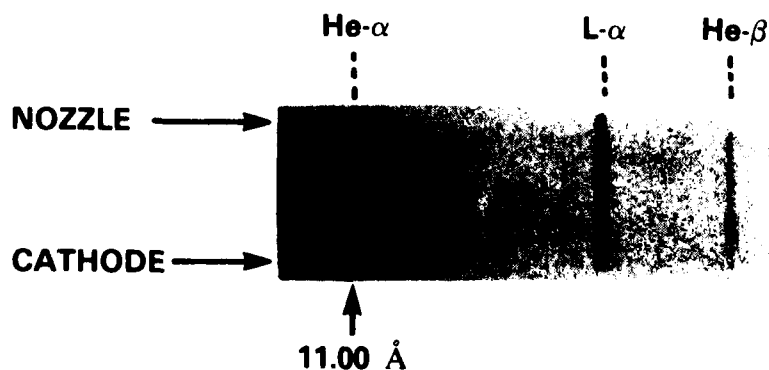


Figure 1. Sodium lines reflected by KAP 002 planes.

## II. LINE WIDTH MEASUREMENTS

The measured full-widths at half maximum (FWHM) for the Na X and Na XI  $\alpha$  transitions (1s-2p) from four spectral traces corresponding to different NaF implosions are listed in Table I. Tabulated are the minimum and maximum values of line width and the measured plasma diameters, D, from the pinhole images. While the observed line widths increase with plasma size, indicating a correlation there is no direct proportionality, thus implying other sources of broadening are present besides the source size effect. In this paper all quoted widths are FWHM.

TABLE I  
Sodium He- $\alpha$  and L- $\alpha$  line widths in Å

Shot	He- $\alpha$ (11.00 Å)	L- $\alpha$ (10.025 Å)	Plasma Diameter in mm
A	0.035 - 0.07	0.025 - 0.047	0.75 - 3.6
B	0.035 - 0.075	0.03 - 0.06	? - 5
C	0.04 - 0.07	0.03 - 0.065	1.1 - 5
D	0.04 - 0.07	0.03 - 0.06	1.9 - 4.8

The line broadening effects inherent to the observation technique (labelled "instrumental" broadening) are twofold. First, there is a line width resulting from imaging with a convex crystal a finite size (diameter) of plasma. Second, a crystal spectrometer has an intrinsic resolving power  $\frac{E}{\Delta E} = \frac{\lambda}{\Delta \lambda_m}$  (with  $\Delta \lambda_m$  the minimum line width reflected) which varies linearly with the crystal rocking curve width (4).

## III. INSTRUMENTAL EFFECTS

To discuss the first broadening effect of reflection from a convex

crystal we consider an emission source of diameter  $D$  and length parallel to crystal axis  $Z$  at a distance  $L$  from the crystal. For practical reasons the incident beam divergence  $d\omega \approx \frac{D}{L}$  is not small enough, in this experiment to be considered parallel. Since  $D \ll L$ , an analytical expression correlating the linear displacement with  $D$  can be derived. We formulated such a relation (5) for a geometry with incident beam (from source center) perpendicular to the spectrograph axis defined as the line connecting crystal and film centers in the incidence plane. Another analytical approximation has been derived (6) for  $r \ll L$ , i.e., a very small diffracting crystal radius  $r \sim 0$ . Under the conditions of observation of the sodium plasmas, (i.e.  $L = 85$  cm), we derived a linespread  $\Delta\lambda$  (Å) of  $0.11D$  (cm), similar to the analytical expression given in the Appendix of (5) for a curved KAP crystal reflection in first order. From the measured plasma diameters  $D$  given in Table I, we expect for the sodium  $\alpha$  lines, a width  $\Delta\lambda$  varying between  $0.05$  Å and  $0.01$  Å. For the sodium line widths measured using KAP crystal second-order reflection and a different geometry we estimated the line spread  $\Delta\lambda$  (Å) to be only about  $0.04 D$  ( $D$  in cm). Thus, in the spectrum obtained with this instrument, for shot A (Table I), the sodium lines should exhibit a width varying between  $0.003$  Å and  $0.0016$  Å only.

Turning now to the other instrument broadening for the minimum line width  $\Delta\lambda_m$  produced by the mica crystal rocking curve, we shall assume a similar resolving power to that obtained with a KAP crystal (with comparable value for  $2d$  spacing in first order as mica). Radiation reflected by a KAP crystal in first order, at the sodium transition wavelengths ( $10$ - $11$  Å), is predicted to spread over  $\Delta\lambda_m \sim 0.005$  Å and  $0.006$  Å respectively (4) (7). For the measurements using a KAP crystal in second order the  $\Delta\lambda_m$  values are smaller by



at least an order of magnitude (7). Therefore,  $\Delta\lambda_m$  is essentially negligible with this instrument.

At this point we conclude that, with this particular experimental set-up, the line width contribution due to instrumental broadening is essentially related to the plasma size and appears significant in the observations with the mica crystal spectrograph (Table I). As mentioned above, by consideration of the values from Table I, the source size effect alone does not account for the measured line widths.

#### IV. PLASMA EFFECTS

We shall, therefore, discuss now the line width contributions due to other mechanisms; namely, the intrinsic plasma broadening processes. First, we need estimate the thermal Doppler broadening and second the so-called pressure broadening due to interaction of the radiating ion with charged neighbors. From the observed spectral line analysis, the plasma temperature and density have been previously estimated (8) to be around 400 eV and in the range 1 to  $5 \times 10^{20}$  electron  $\text{cm}^{-3}$  respectively. For these previously-observed plasma emissions, the sodium line thermal Doppler widths (FWHM) for the Na He- $\alpha$  line is at most 0.0035 Å and, for the indicated electron density range, the pressure broadening appears negligible. In fact, in this case, the linear Stark effect approximation is hardly valid for the L- $\alpha$  transition with a 2p level fine structure larger than the Stark shifts (9). We shall recall here that fine structure splitting amounts to a maximum value of 0.0054 Å for the L- $\alpha$  transition. We note also that, in all sodium spectra the measured line widths are fairly constant throughout the series of both H-like and He-like ions indicating departure from the quasi-static approximation for the ion field (10).

Another mechanism that may broaden the radiation emitted from transient plasmas is the emitting ion motion associated with the plasma macroscopic implosion or expansion velocity. In an imploding plasma, the ionic radial velocities will cause Doppler shifts if the observed K-shell radiation initiates before the so-called stagnation phase on axis. The existing implosion models (11),(12) indeed predict peak ion velocities,  $V_0$ , of about  $2 \times 10^7$  or  $3 \times 10^7$  cm/s respectively for the Gamble II generator. With these models, the K-shell radiated power peaks sharply near the time of maximum ion velocity. Noteworthy, the associated Doppler shifts (estimated for a mean radial velocity) correspond to the observed line widths. The above predicted imploding ion velocities are about 5 times larger than the sodium ion thermal velocities in a plasma at 400 eV.

So far we have not considered opacity broadening which requires a knowledge of the plasma hydrodynamic model in terms of the plasma size and velocity. It appears, however that the static radiative transfer computation might give misleading results in a plasma with large ion streaming velocities. The line photon frequencies from the moving emitters are shifted from the ions absorbing frequencies, thus reducing greatly opacity (13). To support this picture is the experimental evidence of similar line widths for all members of the same Rydberg series. However, from scaling the opacity broadening predictions for an aluminum plasma (14) with comparative 0.4 mm diameter, the Na X He- $\alpha$  line width due to opacity is estimated of the order of 0.007 Å for this size plasma.

The above analysis provides the following estimates for the various contributions (FWHM in Å) to the line widths in spectra from NaF implosions collected with the mica crystal spectrograph:

TABLE II

Contributions to the sodium line widths in Å

Instrumental		Plasma broadening				fine structure (L $\alpha$ only)
rocking curve $\Delta\lambda_m$	Plasma size	thermal Doppler	pressure broadening	opacity	plasma motion	
0.006 (He- $\alpha$ ) 0.005 (L- $\alpha$ )	0.05-0.01	0.0035	-0.001	0.007	Large >0.01	0.0054

These tabulated values emphasize two major contributions to the observed line profiles in the reported experiments: the source size effect (diameter  $D$ ) and a plasma motion effect (velocity  $V$ ). We thus need to compute a line profile by convoluting the azimuthal contribution along the direction of observation with the diffracted wavelength at this location and also to define an "elementary" width of the emitted radiation associated with the other sources of broadening. Taking into account all the various factors discussed above we considered an elementary Gaussian line profile with width (FWHM)  $2\delta = 0.02$  Å for each wavelength  $\lambda$  originating from a volume of plasma at distance  $r$  from axis and moving radially with a velocity  $V(r) = V_0 \frac{r}{r_0}$  with  $V_0$  maximum ion velocity for the plasma radius  $r_0$ . For each plasma annulus with radius  $r$  we thus compute the line profile resulting from the Doppler azimuthal contribution and the image position in the focal plane. The line profile resulting from all  $r$  contributions is obtained by convoluting this line shape with a Gaussian distribution  $I(r)$  of the emitters with FWHM the plasma diameter  $2r_0$  as measured on the pinhole pictures.

The resulting profiles appear similar for line radiation either originating from an implosion of fairly large diameter ( $D \sim 0.4$  cm) or due to

ions moving radially at velocities of about  $5 \times 10^7$  cm/s. In fact, with our model, both contributions are also correlated by the assumption  $V(r) = V_0 \frac{r}{r_0}$ . Therefore, to fit the predicted line shape to the experimental one, both parameters  $V_0$  and  $r_0$  ( $D/2$ ) need to be adjusted maintaining  $2r_0$  close to the measured plasma diameter for K-shell radiation. The elementary line width is also varied, the effect of this parameter value ( $\delta$ ) being shown in Fig. 2.

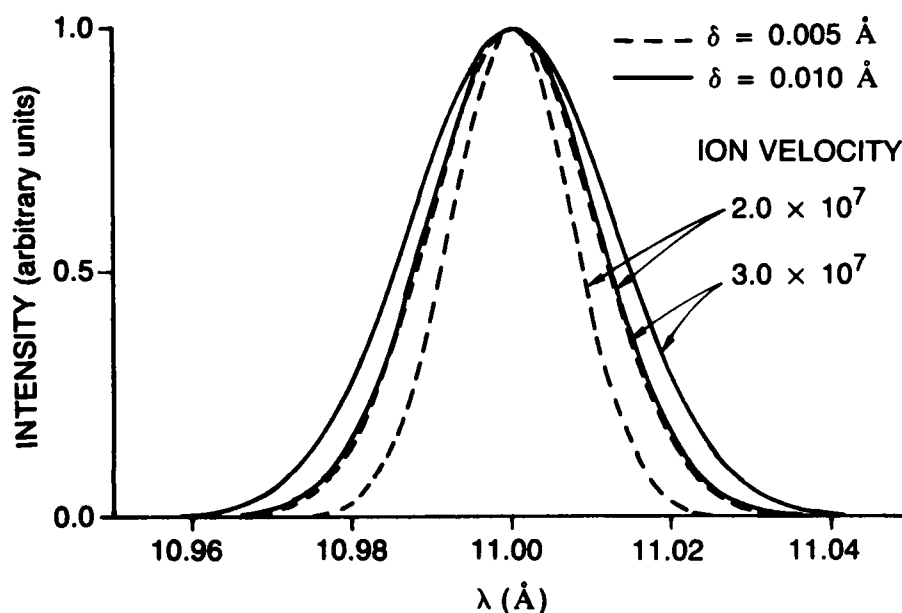


Figure 2. Predicted line profiles (normalized) for Na X He- $\alpha$  using a Gaussian distribution of ions with half-width at half maximum  $r_0=0.05$  cm, two values for the ion velocity at  $r=r_0$  and two values for the line elementary half-width  $2\delta$ .

The four profiles plotted correspond to a radiative volume of 0.1 cm diameter (FWHM for the ion distribution), which is close to the lowest value observed, for two peak ion velocities and for two values of the width  $2\delta$ . Comparing both sets of line shapes we note that the broad wing experimental profiles will better match the computed ones for  $2\delta = 0.02$  Å. Thus, for well-implied

plasmas with  $D < 0.2$  cm the source size contribution is of the same order as the other broadening effects, thus allowing an estimate of the remaining parameter: the peak ion velocity,  $V_0$ . For the plasma regions of larger diameter  $D > 0.1$  cm, the theoretical profiles were fit to estimate  $V_0$  at maximum radius  $r_0$  while maintaining the third parameter  $\delta$  close to 0.01.

The line widths measured on the sodium lines reflected by second order planes in KAP, i.e. with decreased instrumental broadening, are comparable in magnitude, namely between 0.03 and 0.04 Å, except when emitted from plasma regions of less than 1 mm diameter (Fig. 1). We chose some typical He- $\alpha$  and L- $\alpha$  line profiles recorded with this instrument to demonstrate more clearly the ion velocity effect. In Fig. 3a and 3b two examples of fitting the observed sodium He- $\alpha$  and L- $\alpha$  shapes respectively are shown. Since both parameters  $r_0$  and  $V_0$  are adjusted, the ion velocity cannot be determined unambiguously. The fit in Fig. 3a for instance (Na He- $\alpha$ ) is obtained either for a plasma with  $D = 0.2$  cm and  $V_0 = 3.3 \times 10^7$  cm/s or for a larger plasma with  $D = 0.32$  cm (full width of the ion distribution) and peak ion velocities of only  $3.0 \times 10^7$  cm/s.

The observed double-peak profile for the L- $\alpha$  line (Fig. 3b) is not an uncommon feature. It may also occur for the He- $\alpha$  line or for both  $\beta$  lines. It is therefore not related to the L- $\alpha$  fine structure which corresponds to a component separation (0.0054 Å) always several times smaller than the observed splitting. Such profiles were previously observed in neon implosions (5). Most likely they are caused by crystal imaging of a filamentary source or of a very thin plasma shell with minimum radius,  $r_m \neq 0$ . Indeed the predicted profiles for a thin shell plasma exhibit a double-peak image due either to a not-fully imploded plasma ( $r_m \sim 1$ mm) or to a thin plasma annulus (also  $r_m \neq 0$ ) collapsing on axis at velocity  $V_0$ .

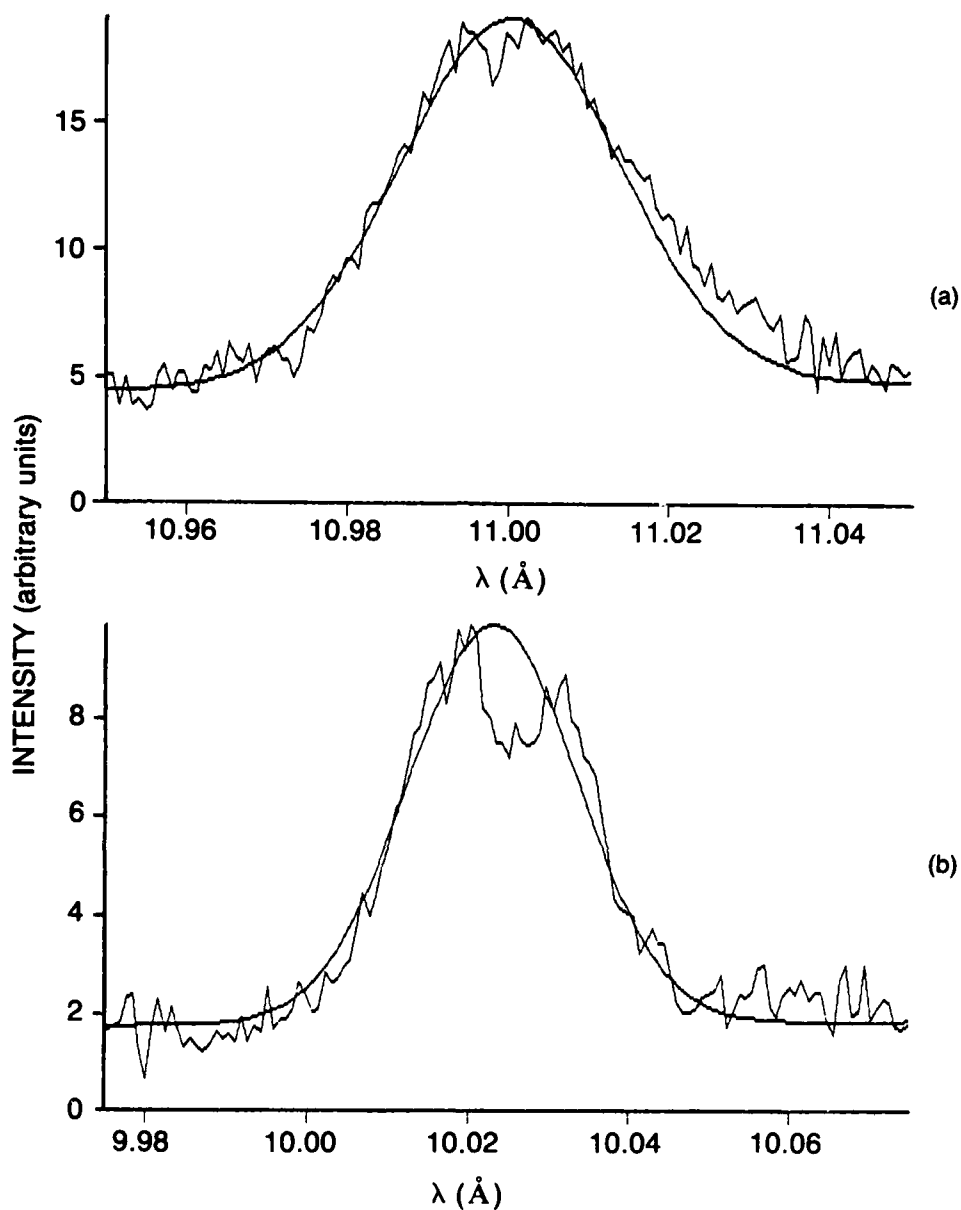


Figure 3. Comparison of observed line shapes with theoretical profiles (smooth curves)

- a - For Na X He- $\alpha$  transition  
fit obtained for  $\delta=0.010$  Å  $N_1(r)=e^{-\text{Log}^2\left(\frac{r}{r_0}\right)^2}$  or  $r_0=0.10$  cm,  $V_0=3.3\times 10^7$  cm/s  
 $r_0=0.16$  cm,  $V_0=3.0\times 10^7$  cm/s
- b - For Na XI L- $\alpha$  transition  
fit obtained for  $\delta=0.008$  Å  $r_0=0.1$  cm,  $V_0=2.6\times 10^7$  cm/s

From the experimental evidence of broader profiles for the He-like lines than for the H-like ones - especially demonstrated in the plasmas of larger D (for instance neon plasmas (5)) - we conclude that the He-like ion emitting region presents a larger diameter and higher ion velocities (corollary). The H-like ion radiation originates from smaller imploded regions. This observation was associated with a temperature variation between both types of ions in the neon plasmas (5).

## V. CONCLUSIONS

We conclude from line profile observations in the NaF implosions that K-shell radiation may initiate before full implosion of the plasma column ( $D > 0.1$  cm) when the ion velocities are still of the order of 2 to  $3 \times 10^7$  cm/s. Similar conclusions with ionic velocity in this range, were reached by Stewart et al. (15) in their study on an imploding argon plasma.

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